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Geology of the PORPHYRY COPPER DEPOSITS
Southwestern North America

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◇ ◇ ◇ GEOLOGY OF THE BINGHAM CANYON PORPHYRY COPPER DEPOSIT, UTAH

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INTRODUCTION

Bingham Canyon is in the central Oquirrh Mountains, the first range of the Basin and Range physiographic province west of the Wasatch front at Salt Lake City. The north-trending Oquirrh Mountains, about 30 miles long, contain the Mercur, Ophir, and Rush Valley mining districts south of Bingham Canyon; these have been silver, lead, and gold producers. The Cottonwood-Park City mining region, in the Wasatch Mountains, is 30 miles east of Bingham Canyon. The Tintic mining district is 40 miles to the south.

History

The West Mountain mining district, site of the Bingham Canyon mine, was formed in 1863 with the staking of the "Jordan" claim on a lead-silver ore exposure in Galena Gulch, a tributary to Bingham Creek. The "Old Jordan" area has remained a scene of concentrated mining activity and is currently part of the immediate access to the copper pit.

Major lead and silver production, from carbonate ores prior to the erection of a mill in 1874 and subsequently from sulfide ores, has continued up to the present time. The district now contains some 400 miles of underground workings in the lead-zinc-silver zone encircling the copper pit, producing several thousand tons of ore per week.

Small shipments of copper ore were made in 1868 and 1869, and copper was recovered as a by-product in the 1870's and 1880's, but the importance of copper in the district was not yet recognized. Emphasis remained upon lead-silver, and, for a short period, on lode and placer gold.

In 1897 a major discovery in the underground workings of the Highland Boy mine, a short distance southwest of the present-day open pit, brought immediate attention to copper and initiated a new phase in the history of the camp. One of the Highland Boy tunnels unexpectedly cut a zone containing 6 percent copper. Less than a month later, a second tunnel intersected a zone containing 25 percent copper. During the early development of the Highland Boy copper mine, shipments totaled 5,000 tons of ore averaging 12 percent copper, $4.00 per ton in gold, and $3.00 per ton in silver. A surge in high-grade copper mining followed, and by 1904 there were three copper smelters operating in the Salt Lake Valley. Production of copper from veins and replacement bodies continued until 1947.

Mining of open-pit porphyry copper ore at Bingham Canyon, the pioneer enterprise of its kind, began in 1906. This important milestone in mining practice was, however, preceded by a number of years of repeated evaluation and appraisal. The first interest in porphyry copper mining dates from 1887 when copper staining at the site of the present Bingham Canyon mine attracted the attention of Col. Enos A. Wall, a successful and experienced mine operator. Subsequent sampling of a nearby tunnel containing disseminated chalcocite and bornite disclosed a 70-foot mineralized zone containing 2.4 percent copper. Col. Wall obtained claims in the area and began considering the development of a large low-grade copper deposit. Support for the project was difficult to obtain; local miners referred to the zone as "wall rock" and practically worthless. The Highland Boy excitement in 1897 intensified Col. Wall's efforts and led him to obtain about 200 acres of ground underlain by mineralized porphyry; these holdings eventually became the nucleus for the operations of the Utah Copper Co.

Investigation of the Wall property was made by several prominent engineers from 1895 to 1903. Estimates of 12 to 25 million tons of 1.6 to 2.0 percent copper ore, which could be concentrated at a 15 to 1 ratio, were considered by mining investors as intriguing but not quite convincing. A profitable operation could not be envisioned, especially considering the large initial capital requirements. In 1903 Daniel C. Jackling, a key figure in the preceding evaluations, succeeded in obtaining the requisite investment capital for the venture; as a result, the Utah Copper Co. was organized with a nominal capital of $500,000. An experimental mill with a capacity of 300 tons per day was constructed at Bingham, and a tunnel was driven into the ore body to obtain bulk test shipments.

In 1904 the Utah Copper Co. was reorganized with a capitalization of $4,500,000, and plans were made for a 6,000-ton concentrator and an open-cut mining operation. Working capital was obtained, although the large-scale operation and the lowgrade ore necessitated revolutionary departures from existing mining practices. Each phase of investment required very precise engineering investigation and careful evaluation.

In 1906 steamshovel operations began and within a few years had entirely supplanted underground mining of porphyry copper ore. The visionary "wall rock" claims had, after 2 decades of constant effort, matured into economic reality.

The Kennecott Copper Corp. acquired stock in the Utah Copper Co. beginning in 1915. By 1936 Kennecott owned all the property and assets of the Utah Copper Co. In 1947 the Utah Copper Division was organized as an operating division of the Kennecott Copper Corp.

The success of the Bingham Canyon mine is widely recognized. About 1 billion tons of ore and 1 billion tons of waste have been mined from the Bingham Canyon open pit. Daily production of ore currently is being increased from 90,000 tons averaging 0.78 percent copper to 108,000 tons. The present ratio of waste to ore is 2½ to 1. The mine, now the largest in the world from the standpoint of both current and aggregate total ore production, is about 1⅝ miles long, 1⅛ miles wide, and half a mile deep.

Metal production from the district through 1960 was:

Copper	About	16,000,000,000 pounds
Lead	About	4,000,000,000 pounds
Zinc	About	1,500,000,000 pounds
Molybdenite	About	500,000,000 pounds
Silver	About	200,000,000 ounces
Gold	About	11,000,000 ounces

Past Geologic Work

The classic geologic report, prior to the epoch of porphyry copper mining, was by Boutwell (4). At that time the district had already attained importance as one of the great camps for applied geology. Boutwell's comments on mineralization trends, localization of ore in limestone, structural control of ore shoots, stratigraphy, and tectonic sequence provided a basis for much subsequent work.

Butler and others (6) published a summary in U.S. Geological Survey Professional Paper 111. Several geologists have published reports based on district study; these include Beeson (2) on the disseminated copper ores, Hunt (12, 13) on bedded limestone ore bodies and district geology, and James and others (16) on district geology.

Publications on specific phases of the Bingham Canyon geology include those by Lindgren (17) on contact metamorphism, Winchell (25) on limestone alteration, Farmin (9) on the Occidental fault system, Schwartz (22) on hydrothermal alteration, Stringham (24) on granitization and hydrothermal alteration, Hunt (11) on hydrothermal alteration, Hansen (10) on the Highland Boy area, and Rose (21) on temperature of ore deposition.

GENERAL GEOLOGY

A metallogenic environment related to the regional intersection or "crossroads" of petrologic and structural trends has long been recognized in northern Utah. The mile-square Bingham stock and its geometrically similar companion to the southwest—the Last Chance stock—are the westernmost in a group of six porphyritic intrusives in folded and thrusted Paleozoic and Precambrian sediments. The group of stocks coincides with the structural axis of the east-west Uinta Mountain uplift, the Bingham and Last Chance intrusives suggesting a western extension of the Uinta trend beyond its topographic and structural termination.

The Bingham and Last Chance stocks are separated from the four easternmost intrusives by the Wasatch fault line, a north-trending break of post-stock age. The Charleston thrust, a west-dipping pre-stock fault, is inferred to pass through the Salt Lake Valley (8) and beneath Bingham Canyon at an unknown depth. The Bingham and Last Chance stocks, projected to depth, would cross the plane of this thrust. Inasmuch as the upper plate of the Charleston thrust is estimated to have been moved scores of miles from the southwest, the alignment of the two stocks with that on the Uinta trend suggests that the major control for intrusion was in the basement and was related to deeper Uinta structure rather than to the shallower structures in the Oquirrh Mountains. The easternmost four stocks on the Uinta trend are in the lower plate of the thrust. The detailed outlines of the Bingham and Last Chance stocks are, however, clearly related to fold-and-fault structures in the Oquirrh Mountains; it is possible that the local pattern of control evolves from thrust plates that lie against the buttress of the old Uinta uplift. Billingsley and Locke (3), on the basis of information available at that time, described the structural environment at the Salt Lake Crossroads as: ". . . the principal structures produced by the intersection of the eastward-thrusting Cordilleran mountain belt and uplift . . . Bingham and Park City reflect in their tear structures the differential progress of Cordilleran deformation in and north of the Uinta crest . . . All result from the complex adjustments necessitated by the intersection of the north-south Cordilleran thrust zone . . . 60 or 70 miles wide, with the resistant uplifted mass of the east-west Uinta uplift 40 miles wide" (3, p. 41–42). More recent work has corrected, clarified, and expanded the geology available to Billingsley and Locke. The postulation of a thrust riding over and against the Uinta mass can, however, still be supported in explaining the details of stock and ore control.

The converging structural elements in the Oquirrh Mountains that controlled the emplacement of the Bingham stock may be described as thrusts, overturns, and tears, which were possibly directed against a buttress, the westward terminus of the Uinta uplift. Two local groups of high-angle faults of considerable displacement also intersect at Bingham Canyon in a geometric pattern related to the porphyritic bodies and to the ore.

The North Oquirrh thrust, 5 miles north of the mine (15), provides a structural and stratigraphic division in the Oquirrh Mountains. North of the thrust, Pennsylvanian and Permian sediments are folded into east-west-striking folds, which plunge to the east. South of the North Oquirrh thrust is a monocline of Paleozoic rocks, dipping gently to the north, upon which a north-to-west-plunging asymmetric fold pattern has been superimposed. The southwest limbs dip gently; the opposing limbs are steep. Progressive steepening in the more northeasterly folds is reflected in vertical beds in the Middle Canyon fold—located immediately southwest of Bingham—in slight overturning in the Bingham syncline, and in sharp overturning in the Copperton anticline. The axial planes of the successive folds also steepen and overturn. Close to the Bingham stock, the axes of the folds trend successively from east-west to north, like spokes in one quadrant of a wheel whose hub lies in the mining district and at the projected western nose of the Uinta structure.

Northeasterly and northwesterly faults, superimposed on the fold pattern, form the Bingham horst and associated faulted blocks.

Control of ore in the district apparently is related to conduits inherent in the structural complex. The relation is best seen in the close spatial agreement of the ore bodies with steeply dipping limestone, bedding shears, and northeast-striking high-angle faults.

GEOLOGY OF THE ORE BODIES

Considering all material above the cutoff grade of 0.4 percent copper and averaging about 0.75 percent copper, the exposed ore body in the pit covers a plan map area of about 18 million square feet. In plan, it resembles an isosceles triangle with a 5,000-foot base and with an apex 7,000 feet to the west-southwest. A few salients extend a short distance from the ore triangle. At least 1,100 feet of ore and capping has been removed from the zone directly above the bottom of the pit. The mined-out part of the ore body has been

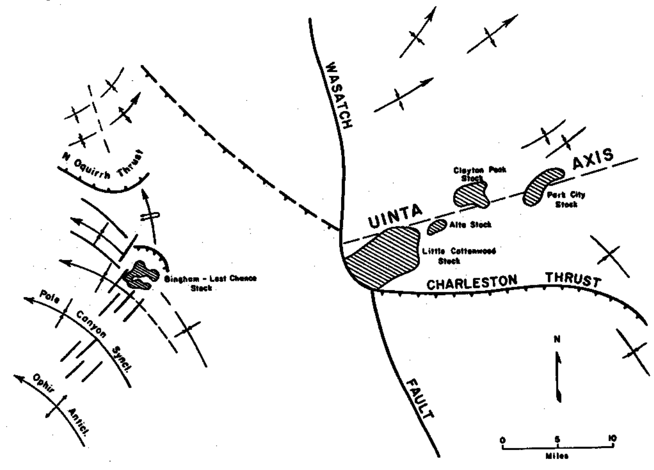

FIGURE 1.—Structural geology map of the Bingham Canyon Region.

essentially uniform in area. The ore being mined at present is nearly all primary and consists of pyrite and chalcopyrite with minor bornite and molybdenite. The ore body is mainly in the Bingham stock, with lesser parts in the adjacent limestone and quartzite.

The triangular plan of the ore body is in striking concordance with two intersecting local fracture systems and with a steeply dipping bedding attitude.

Several dozen northeasterly high-angle fractures with narrow zones of brecciation, comprising the Clipper Peak-West Mountain fault system, correspond to one side of the ore triangle, to a northeasterly elongation of the granite porphyry phase of the Bingham stock, to the trend of narrow dikes, and to the most productive vein deposits.

Northwest-trending structures, fewer in number than the northeasterly system but with greater displacement and intensity, parallel the base of the porphyry copper triangle. Features of major displacement

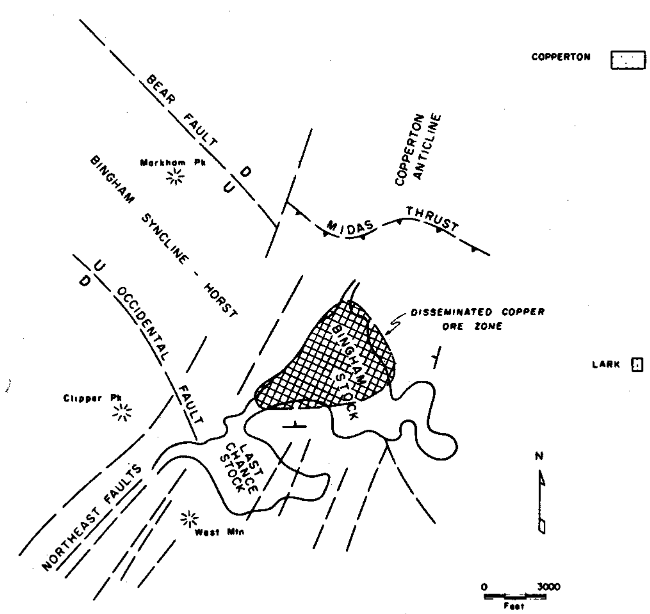

FIGURE 2.—Structural elements at Bingham Canyon, Utah.

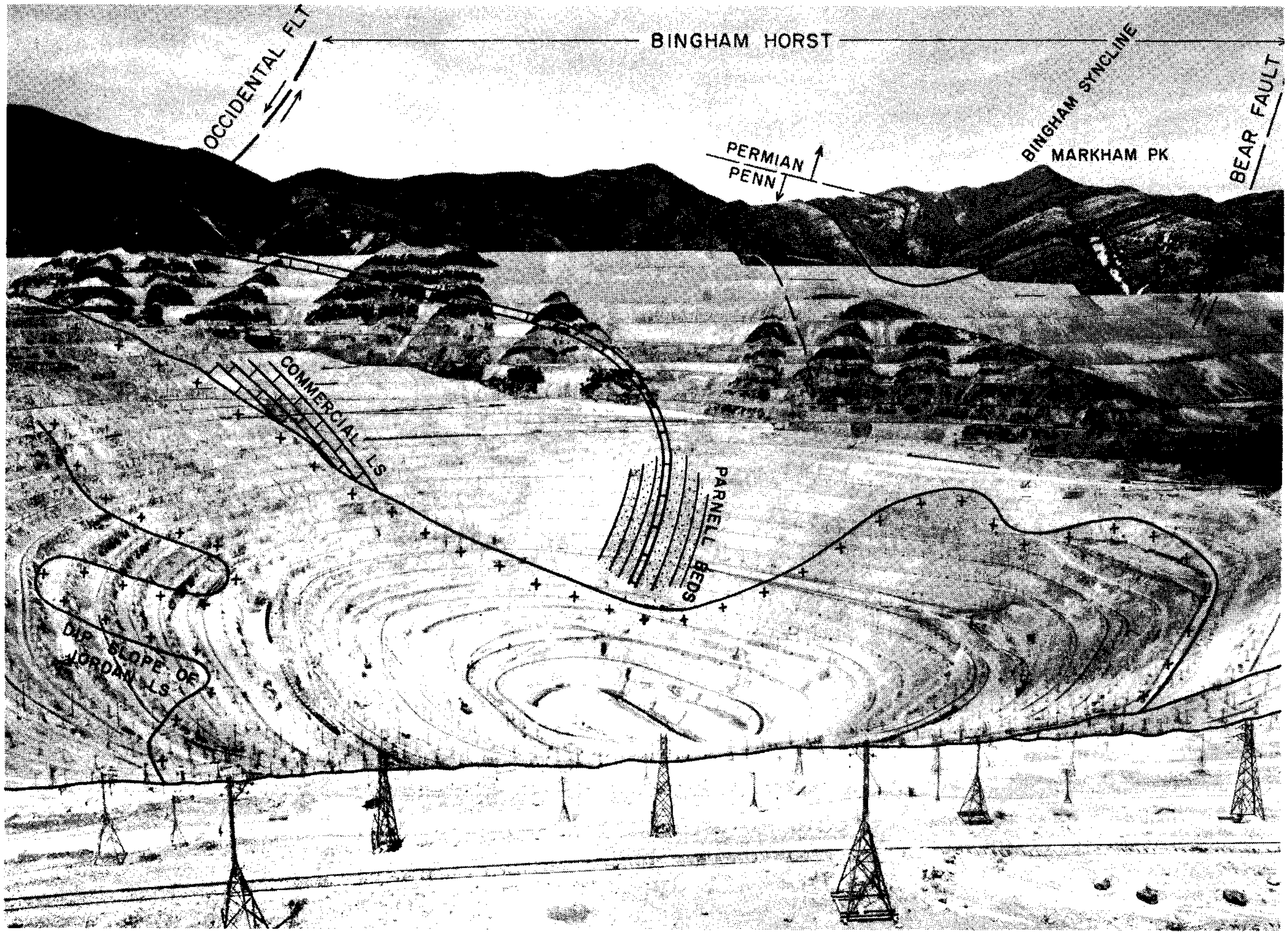

FIGURE 3.—Geologic relations in the Utah Copper Mine looking northwest from the east side of the pit.

in the northwesterly system are the Occidental fault, the Bear fault, and the Midas thrust; the Occidental—a normal fault with a strong topographic expression, a recognized length of 14,000 feet, and a measured throw of 1,500 feet—coincides with the southwestern limit of district mineralization and with the southwestern border of the Last Chance stock. The Bear fault-Midas thrust system attains a length of at least 32,000 feet and a stratigraphic separation on the order of 5,000 feet. The Midas thrust limits important district mineralization toward the north. The Bingham horst, bounded by the Occidental and Bear faults, is a well-defined structural block northwest of the mine area. By projection through the mine area, the horst encompasses the major intrusives and nearly all the important mineralization in the district. The Bingham horst is less apparent in the mine area than to the northwest due to repeated offsetting by the multiple northeasterly faults.

The remaining side of the porphyry copper triangle parallels steeply dipping beds on the limb of the Bingham syncline, a major northwesterly fold that is easily recognized in bedding and topography in the Bingham horst.

The major controls for primary copper mineralization comprise both structural and petrologic elements. The two are not distinctly separable; the local structural pattern has influenced the shape and location of the Bingham and Last Chance stocks, and the stocks have in turn responded to later structural adjustments.

The most striking control for the porphyry copper body is in the relation to the Bingham stock. Ore occurs without apparent selectivity in granite, granite porphyry, and quartz latite porphyry in the Bingham stock and also in the limestone and quartzite adjacent to the stock. At the pit surface, about 32 percent of the ore body is in granite, 27 percent is in granite porphyry, 16 percent is in other intrusive rocks, and 25 percent is in sediments. A part of the Bingham stock, notably the Copperfield lobe to the southeast, is outside the ore body but contains disseminated pyrite. There is no porphyry copper mineralization in the Last Chance stock and associated lobes southwest of the Bingham stock. Minor intrusives outside of the Bingham stock also are barren. The granite and granite porphyry of the ore zone in the Bingham stock provide a contrast to the quartz monzonite and diorite of the

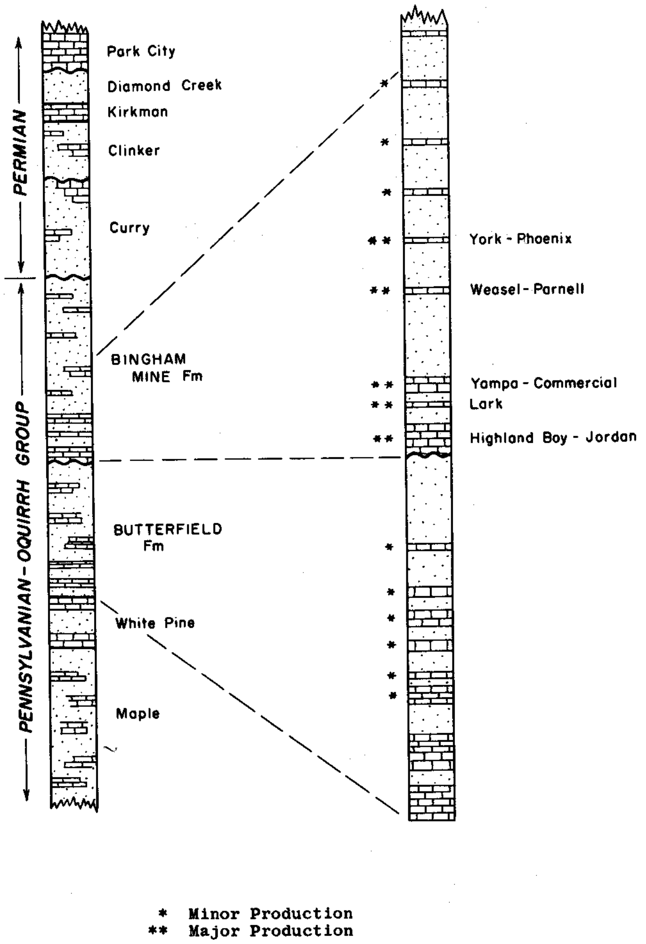

FIGURE 4.—Simplified stratigraphic column, showing production ore zones.

Last Chance stock. The part of the Bingham stock that is outside the porphyry copper body is monzonitic basic, suggesting that the composition of the Bingham stock prior to hydrothermal alteration was closer to that of the Last Chance stock.

Although quartzite and limestone are mineralized in areas adjacent to the stock, metamorphosed limestone tends to be the higher in grade. This is in keeping with the general relation between limestone and the copper-lead-zinc-silver veins and replacements in the surrounding district.

The coincidence of the porphyry copper ore zone with three major structural elements is compatible with ore control by the Bingham stock. The main part of the stock, comprising granite and granite porphyry, is in the copper ore triangle. The barren Copperfield lobe is outside the triangle and is partly separated from the main intrusive body by "islands" of quartzite and limestone.

The ore zone in the Bingham stock contains a network of small fractures spaced a few inches apart. The Last Chance stock, in contrast, is free of close fracturing except in well-defined fault zones.

The location of disseminated pyrite, copper, and molybdenum in successively more centralized zones (16) is concordant with the outlines of the porphyry intrusive and with the shattering of the porphyry and host quartzite. This shattering, common to all the porphyry copper deposits, has been attributed to various causes—tectonic stresses, cooling of magma, and shrinkage due to alteration. It remains as unexplained at Bingham as at other porphyry copper deposits.

Shattering of the quartzite is most intense near contacts with the Bingham stock in ore-bearing zones. Disseminated copper ore, associated fractures in the quartzite, and pyritic mineralization diminish with outward distance from the intrusive contact.

Shattered areas in the quartzite are not mineralized outside the iron and lead-zinc zone, which surrounds the disseminated copper area. Proximity to the "hot center" of porphyry intrusion appears to be essential to sulfide mineralization.

Breccia pipes have been noted in the lead-zinc zone peripheral to the disseminated copper area and in an arc south and east of the copper mine. The pipes are from a few feet to 800 feet in diameter, irregular, and are predominantly vertical; they are composed of subangular to well-rounded fragments of the enclosing formations. The matrix is either crushed wall rock or igneous material.

Primary Sulfide Mineralization

Primary sulfides occur both as disseminations, probably replacements of mafics and magnetite which were formerly present as primary constituents of the host intrusive, and as veinlets. Disseminated sulfides amount to 1 to 4 percent of the host rock. Veinlets are much less important than disseminated sulfides in accounting for copper content. They are, however, apparent on most broken surfaces. The veins are commonly a fraction of an inch thick. Chalcopyrite is the principal copper-bearing sulfide. Bornite and molyb-

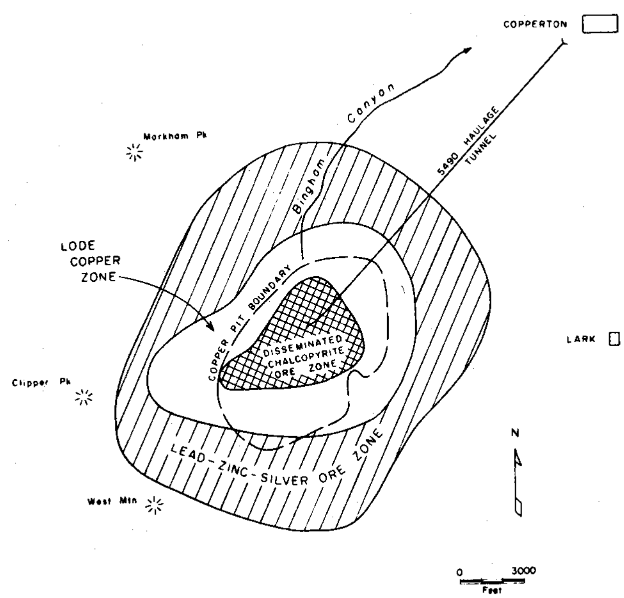

FIGURE 5.—Metal zoning at Bingham Canyon, Utah.

denite are most abundantly localized in the central part of the Bingham ore body. Molybdenite is more commonly associated with veinlets than are the copper minerals. The molybdenite in the ore zone amounts to five hundredths of 1 percent of the rock. Small amounts of chalcopyrite occur as exsolution laths in bornite and vice versa. In addition, small amounts of primary chalcocite have exsolved in the bornite; more rarely, digenite, and possibly covellite, has exsolved from the chalcocite. Although pyrite is a major sulfide constituent of the porphyry ore, it is least abundant in the central part of the ore body, which is thus enveloped by a pyritic halo. Sulfide concentrates, after removal of molybdenite and some pyrite, contain about 60 percent chalcopyrite, 20 percent bornite, 5 percent chalcocite, 1 percent covellite, and 14 percent pyrite.

Enargite-famatinite, galena, sphalerite, and tetrahedrite are present locally in veinlets less than 1 inch wide in sediments on the periphery of the ore body. These sulfides are also characteristic of the fissure and replacement ores that encircle the central Bingham ore body at distances ranging from 1,000 to 10,000 feet. The fissure and replacement deposits are predominantly localized in sediments by stratigraphic and structural controls and are most numerous in the east, south, and west parts of the district. A mineralogical zonation is evident; with increasing distance from the central zone of disseminated copper-molybdenum ore, the veins and replacements grade from dominantly copper ores to dominantly lead-zinc ores. The primary constituents of fissure and replacement ores include galena, pyrite, and sphalerite; there are lesser amounts of chalcopyrite, tennantite, and tetrahedrite and small to trace amounts of arsenopyrite, bornite, boulangerite, bournonite, cinnabar, cubanite, enargite, gold and silver tellurides, magnetite, marcasite, native gold and silver, orpiment, pyrrhotite, realgar, specular hematite, and stibnite.

Oxidation and Supergene Enrichment

Secondary copper mineralization, now practically all removed by mining, was pervasive and was, like the primary ore, associated with the Bingham stock and adjacent sediments. The chalcocite "blanket" was reported to be 200 to 800 feet thick and with an average grade of 1.5 to 2.0 percent copper.

The leached capping, ranging from 25 to 350 feet thick, was affected along with the secondary sulfide zone by two major erosion cycles. During the older cycle, mature topography developed with attendant oxidation. In the more recent cycle, youthful canyons and steep valley slopes developed, and oxidation reached greater depth on the broad divides while some of the earlier material was removed from the lower slopes.

The leached capping contained limonite, hematite, and jarosite with lesser quantities of copper carbonates, copper oxides, and native copper in a matrix of quartz, clay, gypsum, and sericite. Sulfides were sparingly present; Boutwell (4) reported a relative enrichment of gold values in the oxidized zone. In the zone of secondary sulfide enrichment, chalcocite, commonly the sooty variety, and covellite occur as replacements of primary sulfides. According to Beeson (2), covellite was more abundant in the topographically higher part of the enriched zone. Secondary copper carbonates, oxides, and native copper were most abundant in the leached capping that overlay chalcocite-bearing enriched ore. Small quantities of bornite and chalcopyrite replacing chalcocite and covellite were interpreted to be of supergene origin. In general, topographic location of the Bingham ore body has inhibited processes of supergene oxidation and secondary enrichment. Mechanical erosion has proceeded more rapidly than chemical weathering and consequently has limited both the extent and completeness to which the zones of oxidation and enrichment have developed.

Supergene processes have similarly affected the near-surface parts of the peripheral fissure and replacement ores. Oxidation of primary sulfides has resulted in the formation of anglesite, azurite, cerussite, chalcanthite, cuprite, goslarite, hematite, jarosite, limonite, malachite, melanterite, native copper, silver, and gold, tenorite, and probably other minerals. They are commonly associated with supergene carbonate and silica.

Hydrothermal Alteration

The dominant mineralogical changes affecting igneous and sedimentary rocks that are attributable to hydrothermal processes are listed in table 1. The mineralization intensity ranges from strong to weak, as deduced from megascopically discernible features—such as the abundance of sulfides, other alteration minerals, veinlets, and fractures—and generally decreases with distance from the central part of the Bingham ore body. Apart from small to trace amounts of carbonate, chlorite, clay, quartz, and sericite in igneous rocks of the weakly mineralized group, these samples may be considered the unaltered equivalents of the moderately to strongly mineralized groups. Biotite, orthoclase, quartz, and sericite and lesser amounts of albite, calcite, chlorite, epidote, kaolinite, and montmorillonite as veinlets and replacements of primary constituents are the predominant hydrothermal minerals added to or formed in igneous rocks. With the exception of carbonate-bearing units in which tactite minerals may be present in abundance, similar mineralogical effects have been imposed on the enclosing quartzitic sediments. Due to its lesser reactivity, the quartzite was substantially less affected than the igneous rocks. Many of the constituents of hydrothermal alteration and mineralization appear to be zonally distributed and exhibit a tendency to occur in mutually exclusive

TABLE 1

AVERAGE VALUES FOR PRINCIPAL MINERALS COMPRISING IGNEOUS (BINGHAM STOCK AND NEARBY INTRUSIVES) AND SEDIMENTARY ROCKS FROM ZONES OF DIFFERING MINERALIZATION INTENSITY (BASED ON THIN-SECTION DATA AND INFRARED AND X-RAY DIFFRACTION ANALYSES)

Rock type		Igneous			Sedimentary	
Mineralization intensity	Strong	Moderate	Weak	Strong	Moderate	Weak
Number of samples	23	6	12	6	27	71
Mineral (percent)						
Quartz	20.7	19.8	19.3	73.8	89.3	89.5
Potash feldspar	31.7	25.3	9.0	3.2	1.7	1.4
Plagioclase feldspar	7.3	9.5	36.4	—	—	—
Amphibole	—	2.0	.5	.5	.5	1.2
Pyroxene	—	—	4.0	13.7	.3	trace
Biotite	21.0	15.8	7.2	4.7	trace	—
Sericite	7.4	10.7	8.8	1.5	1.3	1.1
Chlorite	2.3	6.5	4.7	—	2.5	.8
Talc	—	—	—	—	1.5	.4
Montmorillonite	trace	2.3	3.5	—	trace	.6
Kaolinite	.9	1.0	.2	.3	1.3	.4
Carbonate	—	—	.2	.2	.9	2.3
Epidote	—	.3	1.0	1.5	.1	trace
Garnet	—	—	—	present	present	—
Magnetite	trace	.3	1.3	present	present	—

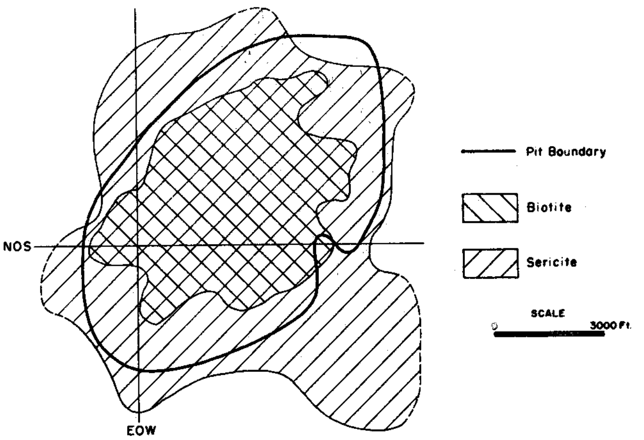

FIGURE 6.—Distribution of hydrothermal biotite and sericite.

association regardless of host rock. Although a number of investigators, including Creasey (7) and Burnham (5), have utilized the facies concept in describing hydrothermal alteration at Bingham and elsewhere, the following discussion based on the occurrence, abundance, and distribution of individual minerals is more objective; possible facies grouping is left to the reader. Where the distributions of selected minerals are illustrated, they are given for both igneous and sedimentary rocks.

The distributions of hydrothermal biotite and sericite are shown in figure 6. Biotite is restricted to the ore zone in the igneous and sedimentary rocks. It is characteristically fine grained and occurs as veinlets and in replacement nests and clusters. Hydrothermal biotite locally may exceed 20 percent in sediments or 35 percent in igneous rocks, exclusive of primary igneous phenocrysts that constitute the only variety in the rock outside the ore zone.

The term hydrothermal sericite as used refers to a fine-grained nonpleochroic micaceous mineral that may include hydromuscovite, illite, and mica-clay mixed-layer minerals. Its distribution is widespread in the mineralized area. In the ore zone it occurs as veinlets and masses replacing plagioclase and potash feldspar in igneous rocks and detrital microcline grains in sediments. Not uncommonly, the sericite is intermixed with kaolinite. In igneous rocks outside the ore zone, sericite is present chiefly as an alteration product of the primary mafic constituents. A few igneous rocks from all mineralization groups are composed almost entirely of subequal amounts of quartz and sericite.

Chlorite exhibits two principal modes of occurrence: 1. as fine-grained veinlets and replacement masses commonly associated with hydrothermal biotite in igneous and sedimentary rocks in the ore zone, and 2. as an alteration product of the primary mafic constituents of weakly mineralized igneous rocks outside the ore zone.

The distributions of kaolinite and montmorillonite are shown in figure 7. Neither are appreciably abundant; the concentration of kaolinite rarely exceeds 5 percent. Its distribution is largely confined to mineralized igneous and sedimentary rocks in and near the ore zone where it is present in veinlets and as intergrowths with sericite replacing feldspar. Montmorillonite predominantly is localized on the borders of the ore zone, and its distribution is erratic and largely peripheral to that of kaolinite. It is commonly associated with chlorite and sericite, particularly as a replacement of mafic and feldspar constituents of igneous rocks. The concentration of montmorillonite, where present, seldom exceeds 15 percent.

Apart from its occurrence as a primary constituent of both igneous and sedimentary rocks, orthoclase of hydrothermal origin (fig. 8) has been added to the ore zone in the Bingham stock and enclosing sediments. It is generally 1 to 3 mm long and may be present in veinlets or as replacement rims of plagioclase feldspar in igneous rocks. Replacement mosaics of quartz and orthoclase with a grain diameter of about 1 mm are common, and according to Stringham (24), the feldspar networks developed in sediments may contain albite intergrown with orthoclase.

Quartz has been added to all the rocks of the district as veins and veinlets. In the ore zone orthoclase may

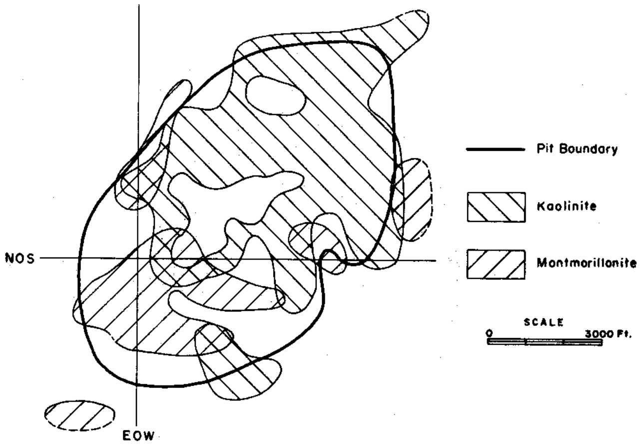

FIGURE 7.—Distribution of hydrothermal kaolinite and montmorillonite.

be associated with the quartz in veinlets and the replacement mosaics described above.

Calcite and epidote are present with small amounts of albite, chlorite, and clay replacing the mafic and plagioclase constituents of less intensely mineralized igneous rocks that partly surround the district and lie outside the ore zone. Although many of these minerals are not as extensively developed in sediments, if at all, collectively they are interpreted to represent a propylitic halo of weak hydrothermal alteration which separates the central part of the Bingham district from dominantly unaltered and unmineralized terrain.

Trends evident in table 1 indicate that the hydrothermal additions to igneous rocks have occurred at the expense of the primary constituents. With the exception of actinolite locally developed in the Bingham stock adjacent to limestone units, biotite as relict phenocrysts, and plagioclase feldspar, the primary magnetite, mafic, and plagioclase feldspar minerals of igneous rocks have undergone near-complete destruction in the more intensely mineralized parts due to replacement additions of potash feldspar, quartz, and other minerals. Although the principal intrusive units of the Bingham stock are classified as granite, porphyritic granite, and granite porphyry, partial modes of many igneous samples used in recent studies utilizing the abundances of quartz, orthoclase, and plagioclase feldspar recalculated to 100 percent (fig. 8) indicate that the classification may have been biased as a result of hydrothermal effects. With increasing intensity of mineralization the intrusives grade from granodiorite and quartz diorite outside the ore zone through quartz monzonite to granite within the ore zone. Hydrothermal additions of orthoclase and quartz, commonly at the expense of plagioclase feldspar, are responsible for the trend. Although Stringham (24) has proposed that the granite originated by granitization of sediments prior to intrusion of the granite porphyry, geologic and mineralogical evidence does not support this hypothesis, and the writers favor a magmatic origin for all components of the Bingham stock. The large proportion of quartz in averages for each mineralization group reflect samples composed chiefly of quartz and sericite that are not illustrated, as they fall in the upper part of the ternary diagram. The trend may be influenced partly by rock-type effects due to the inclusion of many possibly more mafic samples from the Last Chance stock and nearby undifferentiated intrusive bodies in the weakly mineralized group. However, this effect is believed to be small, as the trend also is present in samples of the Bingham stock and is clearly attributable to hydrothermal processes. Moreover, the spectrum of rock types in figure 9 is similar to that previously reported by Stringham (24).

Except for their more limited distribution, the nonsulfide constituents formed by hydrothermal processes in sediments in and adjacent to fissures and replacement ores exhibit many similarities to those of the central disseminated copper-molybdenum ores.

Although gangue-mineral associations are varied and complex, the calcium-magnesium silicates or tactite assemblages are predominantly localized in sediments nearest the Bingham stock with the copper-replacement ores. With increasing distance from the central Bingham stock, alteration in carbonate members grades from tactite through marble to weakly altered or unaltered limestone.

Although variable amounts of supergene gypsum, kaolinite, montmorillonite (nontronite), quartz, and sericite, in association with carbonates, oxides, and sulfates derived from the oxidation of sulfides, have been noted in previous studies of the original leached capping and oxidized parts of fissure and replacement ores, the overall distribution of nonsulfide constituents as described above is believed to be related to primary hydrothermal effects, as it is supported by subsurface mineralogical data.

GEOCHEMISTRY

Chemical effects related to hydrothermal processes are summarized in table 2. Aluminum, magnesium, potassium, and silicon are enriched in igneous rocks from the more strongly mineralized zone. This enrich-

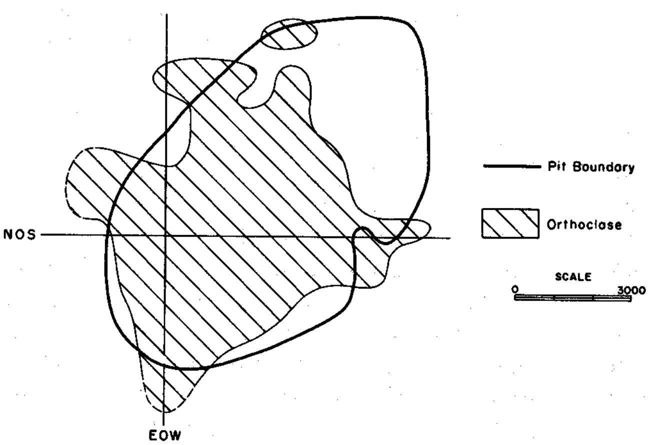

FIGURE 8.—Distribution of hydrothermal orthoclase.

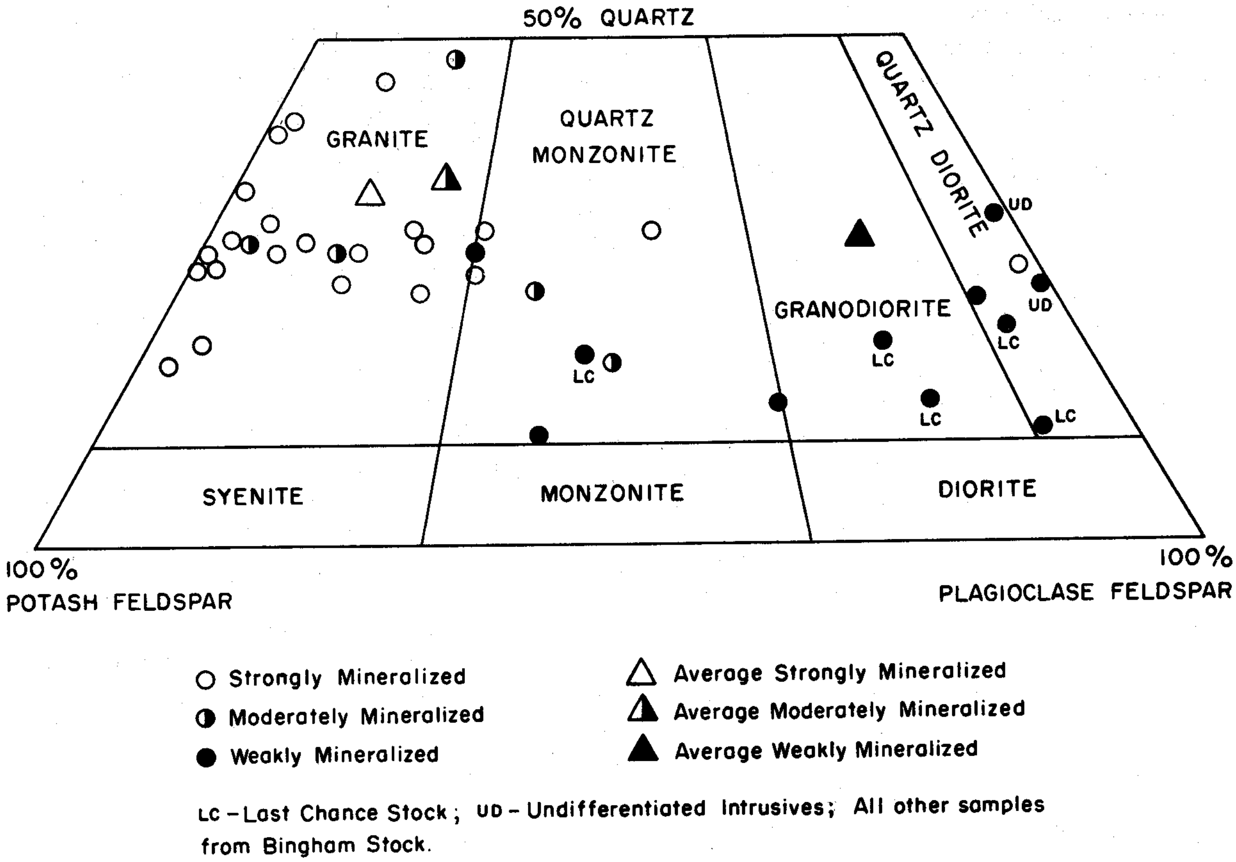

FIGURE 9.—Variation of intrusive rock types with differing mineralization intensity. (Diagram partly modified after Johannsen, 1933, Petrography, Volume I: Univ. of Chicago Press; and Travis, 1955, Classification of Rocks: Quarterly of the Colorado School of Mines.

ment is consistent with hydrothermal additions of biotite, kaolinite, orthoclase, quartz, and sericite previously described. Depletion of calcium, iron, and sodium in strongly mineralized igneous rocks is correlative with the hydrothermal destruction of primary mafics, magnetite, and plagioclase feldspar. The iron low in strongly mineralized igneous rocks suggests that additions of biotite and sulfides were quantitatively insufficient to overcome losses caused by the destruction of primary mafics and magnetite. Although large variations in the primary carbonate and quartz content of sediments make it difficult to properly interpret calcium and silicon values, the data in table 2 indicate that the major elements were added to or remained stable in strongly mineralized sediments. These trends are largely consistent with the previous results of Lindgren (17) and Winchell (25) who showed that silication of carbonate host rocks adjacent to replacement ores was accompanied by a gain of aluminum, iron, magnesium, silicon, sodium, and sulfur and a loss of calcium and carbon. The apparent greater reactivity of sediments to hydrothermal additions of elements, as compared to igneous rocks, is attributed to small amounts of carbonate originally present that were largely converted to calcium-magnesium silicates during mineralization. Although appreciably less abundant, gallium, strontium, chromium, and rubidium (data not given) exhibit trends indicative of a covariant relation with aluminum, calcium, iron, and potassium, respectively.

TABLE 2

AVERAGE VALUES FOR SOME MAJOR ELEMENTS IN IGNEOUS (BINGHAM STOCK AND NEARBY INTRUSIVES) AND SEDIMENTARY ROCKS FROM ZONES OF DIFFERING MINERALIZATION INTENSITY (BASED ON EMISSION SPECTROGRAPH AND X-RAY FLUORESCENCE ANALYSES)

Rock type		Igneous			Sedimentary	
Mineralization intensity / Number of samples	Strong 23	Moderate 6	Weak 12	Strong 6	Moderate 27	Weak 71
Element (percent)						
Aluminum	6.61	5.17	5.92	1.67	1.38	0.93
Calcium	.33	.43	2.00	2.10	.98	1.43
Iron	2.51	3.70	3.44	1.62	1.23	1.18
Magnesium	1.53	.97	.85	1.37	.56	.37
Potassium	4.96	4.67	3.25	.65	.57	.47
Silicon	27.1	20.7	21.8	27.9	26.8	29.9
Sodium	1.64	1.25	1.80	.07	.04	.04

Geochemical data for a variety of minerals of primary igneous and hydrothermal origin have been obtained from diverse studies by ourselves and others. Parry and Nackowski (20) reported average concentrations of copper, lead, and zinc in biotite from the Bingham stock (disseminated ore) to be 1, 900, 11, and 63 ppm, respectively, whereas average concentrations of these elements in biotite of the nearby Last Chance stock (sparse fissure ores) are 110, 48, and 160 ppm, respectively. Although high copper values may be caused in part by sulfide contamination in addition to lattice substitutions in biotite, the results are interpreted to represent different base-metal concentration populations for the Bingham and Last Chance stocks. Average lead contents of 44 and 80 ppm were determined by Slawson and Nackowski (23) for potash feldspars of the Bingham and Last Chance stocks. Comparison to the assumed 25 ppm average lead content of potash feldspar indicates enrichment that is correlated with nearby lead ores associated with these igneous rocks. Rose (21) has reported the iron sulfide content of sphalerite from fissure and replacement ores to range from 0.2 to 16.7 percent. A poorly developed vertical zonation attributed to a temperature gradient and characterized by decreasing iron sulfide values with increasing altitude was found in one mineralized limestone unit.

Relation of Ore Mineralization

Igneous activity in the Bingham district was preceded by episodes of folding and faulting. Intrusion of the Bingham stock, Last Chance stock, and smaller intrusive masses largely pre-dated extrusive activity. The Bingham granite has been dated as 45 m.y. and 49 m.y. by lead-alpha and potassium-argon (written communication, R. L. Armstrong) methods, respectively, and the Last Chance stock has been dated as 37 m.y. by the lead-alpha method. Owing to errors and other uncertainties largely inherent in the lead-alpha method, the three ages are not at present considered to be significantly different. Renewed displacements along the northeast fault system and locally intense faulting and fracturing in the Bingham stock and enclosing sediments preceded hydrothermal mineralization. The constituents of hydrothermal alteration and mineralization are zonally related to the Bingham stock; neither the nearby Last Chance stock nor breccia pipes have appreciably influenced the localization of ores. Strontium-isotope abundance data suggest that the Bingham stock was derived from a deep-seated magma from the upper mantle or lower part of the crust. With less certainty a similar source for the hydrothermal fluids may be inferred from sulfur-isotope abundance data.

The formation or introduction of hydrothermal clay, mica, orthoclase, quartz, and tactite minerals preceded or was contemporaneous with sulfide mineralization. Stringham (24) has described seven distinct hydrothermal stages, which are largely in agreement with the above generalization.

At least a part of the molybdenite may have been deposited early in the sulfide stage, whereas textural relations suggest that pyrite was deposited continuously throughout the sequence of sulfide mineralization. However, more detailed paragenetic relations are partly obscured by post-mineralization deformation and faulting in and along fractures and veinlets.

Summary and Comments on Origin

The Bingham Canyon district is an outstanding example of a large zoned hydrothermal ore complex with local and regional structural control and with definite intrusive associations.

In the porphyry copper body, sulfide zoning is reflected in a central chalcopyrite-bornite-molybdenite association grading into a peripheral chalcopyrite-pyrite association and into a pyritic halo. In vein and replacement deposits outside the porphyry copper body, zonal relations are apparent with copper mineralization grading outward into lead-zinc-silver mineralization and into a weak outer manganese zone. Vertical zoning has been suggested by Lindgren (18) in lead-silver veins that increase in copper content with depth.

A wide range in hydrothermal conditions is suggested by the variety of ore and gangue minerals in the lead-zinc-silver zone.

Primary hydrothermal mineralization in the central zone of disseminated copper-molybdenum ore and outer zone of fissure and replacement lead-zinc ores was attributed to mesothermal processes by Lindgren (18), whereas the intermediate zone of dominantly copper replacement ores in silicated limestone hosts was ascribed to pyrometasomatic processes. The distinct zoning of ore-bearing sulfides suggests a common source for the hydrothermal fluids that emanated outward and upward from the Bingham stock. The zonal distribution of the ores and associated nonsulfide constituents formed by alteration and mineralization was probably governed largely by the chemistry of the host rocks and hydrothermal fluids as well as by temperature.

The connection between tectonics, intrusive pattern, and ore at Bingham is classic. The mineralized Bingham stock, apparently derived from a deep-seated source and subjected to intense structural adjustment, is characterized by intense and closely spaced fracturing in the ore zone, but the neighboring Last Chance stock is lacking in closely spaced fractures and is barren.

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